FINAL REPORT

Key West Harbor Area Background Turbidity Monitoring, October 2003

Delivery Order 0002
Contract DACW17-03-D-0016

Prepared for

U.S. Department of the Army
Corps of Engineers, Jacksonville District
Prudential Office Building
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Jacksonville, Florida 32207-8175

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Executive Summary

Turbidity has been selected to be an indicator of water quality during the future dredging at Key West Harbor. Turbidity will be monitored for operational compliance with permit requirements. Because there was little existing turbidity data for the area, this background turbidity monitoring program was designed and implemented to provide information that would be directly relevant to the operational control of dredging activities and the protection of marine resources.

After plans were completed and field work had begun to establish and monitor seven stations, the City of Key West, with approval of the Jacksonville District US Army Corps of Engineers Corps, funded the concurrent monitoring of three additional stations. Data from the three additional stations, Stations E-KWT03-3, -4, and -5 in the Mallory Dock area, provided for a more comprehensive investigation of the turbidity regime throughout the harbor area, particularly with regard to the impact of cruise ship traffic. The same methods, procedures and the instrumentation were used at all ten stations; consequently, the quality of data should be consistent and indistinguishable for all of the stations.

Ten monitoring stations were established to record turbidity measurements at two-minute intervals during most of the month of October 2003. Stations were located from the Gunner Dock at the bay on Fleming Key through the Key West Harbor area to the southeastern end of the Cut "A" Range, approximately two miles south of the island of Key West (Figure 1). In this general area, water current directions and speeds were measured using a drogue with attached surface float.

Turbidity data were plotted with information on tides and weather as well as cruise ship arrivals and departures in order to identify factors that influence changes in the distribution and magnitude of turbidity. The purpose of identifying factors that cause or are associated with predictable changes in turbidity patterns was to apply this understanding to the operational control of dredging activities. In this manner, dredging related contributions to turbidity levels could be better defined and measured and marine resources could be better protected from dredging effects.

Turbidity monitoring was performed using Hydrolab® DataSonde 4a instruments equipped with 4-Beam Turbidity Sensors designed for measurement of low levels of turbidity. The accuracy and precision of these units were found to be acceptable for operational monitoring. Some problems with baseline calibrations and power losses were experienced during the unattended operation of these instruments. The problems encountered during unattended monitoring should be eliminated during operational monitoring when field personnel use these sensors with similar equipment and real-time information displays.

The directions of current flow in the harbor channel between Key West and the two islands to the west were found to be tidally driven and predictable (Figure 16); however, water movement in the channel area south of Key West was found to vary and appeared to be controlled by tides and wind (Figure 17). At times, the rising tidal flow south of the island of Key West was measured moving to the west instead of a more northward direction. This investigation has been useful to identify the importance of wind and tide in controlling the direction and speed of water flow in this south-of-island area. However, based on the limited information collected in October 2003,

the circumstances under which wind will influence or dominate tidal forces cannot be determined.

Currents were seen to flow in curving, nonlinear lines. Water current speeds typically averaged between 0.4 and 1.8 miles per hour (mph). In 10 to 20 mph winds, the surface float on the drogue may have biased the measurement of water current speed and/or direction with an impact of 0.1 to 0.2 mph (Figures 15 and 16).

During a period of calm weather with winds averaging less than 5 mph, tidal turbidity patterns were observed at most stations. This tidal pattern displayed broad peaks that coincided with low tides and had turbidity maxima that were 1 to 3 NTUs above the high tide values (Figure 8).

During the same calm weather period, a different pattern was observed in the protected waters at Truman Harbor and the Fleming Island Gunner Dock. This second pattern occurred on a daily basis when turbidity levels would rise and fall approximately 2 to 3 NTUs between 0600 and noon (Figure 9). This pattern was not observed at the other stations where water currents are greater. This pattern might be attributed to the migration of marine organisms in the water column.

Visually discernible water masses were observed throughout the area. Weed lines were observed flowing through the channel area between Key West and the two islands west of it (Figure 2). However, insufficient information was collected to determine if there are occurrences of turbidity differences in water on either side of these weed lines. If such differences occur, then the lack of information may seriously impede accurate interpretation of future compliance monitoring data.

Other observable water masses were associated with 10 to 20 mph winds from the south or east. These turbid water masses were photographed and detected with monitoring equipment as they entered the harbor area and flowed northward by the cruise ship docking area and then Fleming Key (Figure 3 through 6). These events sometimes would last through the entire rising tide with turbidity levels rising 5 to 10 NTUs above previous slack tide readings (Figures 10 and 11). While naturally-occurring turbid water masses appear to be created outside of the harbor, their movement through the harbor was seen to flow at speeds similar to those measured during normal tidal flows.

Turbidity plumes associated with the prop wash of cruise ship bow and stern thrusters were photographed and measured (Figures 7, 12, and 13). These water masses appear to have higher maximum values but are much shorter in duration. Elevated turbidity readings were observed to last for approximately 15 to 30 minutes after cruise ships passed by monitoring stations on their way to or from the docking areas (Figure 14).

This background turbidity monitoring effort was designed to generate data from areas that potentially would be affected by future dredging operations. It was intended to identify examples of phenomena, e.g. weather, tides, and ship traffic, which might relate to the interpretation of future compliance monitoring of dredging operations. This effort has been successful in identifying several such phenomena during October 2003. However, it should not be assumed that all major and important phenomena relative to future dredging and water quality compliance monitoring have been identified.

A detailed and labor-intensive evaluation of the entire data set was not intended and is not provided. Consequently, only selected turbidity graphs are presented and discussed in the body of this report. However, all collected turbidity data have been graphed and are included in Appendix A.

1 Introduction

The primary purpose of this turbidity monitoring project was to collect baseline data for turbidity levels in Key West Harbor and the Entrance Channel. Data were collected to document changes in turbidity levels associated with natural events (e.g., tidal movement of different water masses, typical weather patterns, and storm events) and routine harbor usage (e.g., cruise ship movements). These data were evaluated to identify situations where horizontal variation of turbidity would be expected to occur from actions unrelated to future dredging activities.

Of secondary importance, this field effort allowed direct observation of boundaries of different water masses to be made as well as measurement of water current speed and direction. Water currents and the movement of differing water masses are important factors that should be addressed in the operational turbidity monitoring program that will be established for dredging of the harbor and entrance channel.

After plans were completed and field work had begun to establish and monitor seven stations, the City of Key West, with approval of the Jacksonville District US Army Corps of Engineers Corps, funded the concurrent monitoring of three additional stations. Data from the three additional stations, Stations E-KWT03-3, -4, and -5 in the Mallory Dock area, provided for a more comprehensive investigation of the turbidity regime throughout the harbor area, particularly with regard to the impact of cruise ship traffic. The same methods, procedures and the instrumentation were used at all ten stations; consequently, the quality of data should be consistent and indistinguishable for all of the stations.

2 Methods and Procedures

2.1 Turbidity Monitoring

Turbidity monitoring was conducted with Hydrolab® DataSonde 4a units equipped with 4-Beam Turbidity Sensors. These sensors were designed to monitor the low levels of turbidity normally encountered in drinking water. The units were also equipped to collect temperature and conductivity data. Although not calibrated with standards during the monitoring period, conductivity data were collected to serve as markers to indicate when the units were retrieved, that, conductance of air and deionized water is near zero compared to the approximately 50 to 60 millisiemens per centimeter for area seawater. These field instruments were programmed to collect data at two-minute intervals.

Standard operating procedures for the calibration and servicing of the Hydrolab® units appears in Appendix B. The following is a summary of the procedures used.

Hydrolabs were deployed for 2-day intervals. Prior to deployment they were cleaned and calibrated using serial dilutions of a 4000 NTU Formazin primary standard. The units were programmed to collect data every two minutes and the program was given a distinct filename indicating the station and date. Upon retrieval, units were checked with 3 to 4 calibration check standards to document the quality of data being generated at the time of retrieval. After cleaning, servicing, calibrating, and reprogramming, units were typically redeployed at the stations from which they had been retrieved. Instruments suspected of malfunctioning were removed from service and replaced with available backup instruments.

Turbidity monitoring stations were constructed by assembling protective housings using 4-inch diameter PVC (polyvinyl chloride) pipes mounted onto navigational aids or fixed structures, such as docks. Hydrolabs were inserted into the PVC pipes initially to a depth of 10 feet below the water surface where the sensors would protrude from the end of the pipes. At stations where the strong currents damaged the protective structures, the PVC casing and sensors were fixed at five feet below the water surface.

Data were downloaded from the Hydrolabs into notebook computers immediately upon retrieval. Collected data were imported into a spreadsheet program and were reviewed for any notable and/or correctible error messages. Data were saved to a floppy disc for redundancy before deleting the running program and creating another program.

Turbidity monitoring stations were established at 10 locations between the southeastern end of Key West Harbor Cut "A" and the Gunner Dock at Fleming Key. Each monitoring station was given a prefix of E-KWT03 for "Environmental- Key West Turbidity 2003." The individual stations were assigned numbers of 1 to 10 going from north to south. Figure 1 shows the location of each station. Table 1 shows the location of each station and provides a description of it.

2.2 Observing Water Masses and Currents Boundaries

Before background turbidity monitoring began, reports were received that occasionally water masses of differing water qualities, e.g. turbidity levels, meet in and around the Key West Harbor area. It also was reported that such water masses were tidally driven. Because water quality compliance during dredging operations will include turbidity monitoring points that are "up current" and "down current" relative to the point of dredging, it is important to identify situations where differing water masses may complicate the interpretation of operational monitoring data.

While crossing the harbor area for background turbidity monitoring and current measuring activities, the field team was observant for visually discernable differences in the appearance of the water that might indicate the presence of water masses of differing water quality. When such instances were encountered, the scene and circumstances were to be described and photographed.

2.3 Monitoring Water Currents

A secondary objective of this investigation was to obtain information on water currents at mid-depth while ensuring that no marine resources would be damaged by the drogue used for monitoring. Consequently, the monitoring depth selected was 10 to 13 feet below the surface except in the shallow water near the Fleming Key Dock, where a depth on 7 to 10 feet was used.

To measure water current speed and direction of flow, a subsurface drogue was attached to a much smaller surface float equipped with a differentially-corrected global positioning system receiver (DGPS). The design concept for the drogue-float was to suspend the body of the drogue in the water column 10 to 13 feet below the surface and to minimize the size of the float in order to reduce the influence of wind and surface currents. The effort to expedite background turbidity monitoring, the primary objective, resulted in a reduced level of effort to refine the current-monitoring drogue-float design.

The drogue was made from a 70-gallon, cylindrical plastic drum in which holes were cut into both ends to facilitate filling and emptying of water. An 8-pound weight was secured to the bottom end of the drum and the top end was attached to the surface float with a plastic-coated wire cable. Halfway between the drogue and the float, weights were attached to ensure that the surface float would be vertically oriented most of the time.

The surface float consisted of a 5-foot length of ½-inch PVC (polyvinyl chloride) pipe to which boat fenders and a foam float were attached. The float and weights were adjusted to ensure proper vertical orientation and adequate visibility in rough seas. A Garmin Corporation Model GPS76 DGPS was placed in a water-tight plastic container and attached to the top of the PVC pipe.

The DGPS was enabled to use WAAS (Wide Area Augmentation System) data to differentially correct position data using the NAD 83 datum. During use, the unit was set to record data at 20-second intervals. Information recorded by the GPS76 included time, date, location, distance traveled between readings, as well as speed and direction traveled between readings.

The drogue-float was deployed for periods ranging from approximately 15 minutes to over one hour. After recovering drift information from the DGPS, the data were evaluated for potential groundings. Data recorded during drogue release and retrieval were removed from the data set to remove impact and potential bias of boat drift and water movement caused by the boat motor.

2.4 Collection of Ancillary Information

The water level data were retrieved for the station located in Truman Harbor. Data were collected by the National Ocean Service (NOS) at six-minute intervals and reported using Eastern Standard Time. These data were converted to Eastern Daylight Time to be consistent with the rest of the report. Preliminary water level data was obtained from the following NOS website:

http://www.co-ops.nos.noaa.gov/cgi-bin/plotqry.pl?stn=8724580+Key+West+,+FL&flag=1

Hourly weather data was obtained from the National Weather Service for the Key West Airport. The airport is located approximately 3 miles east of Truman Harbor. The website from which the weather data were obtained was:

http://www.srh.noaa.gov/data/obhistory/KEYW.html

Cruise ship arrival and departure information was obtained from a cruise ship schedule produced by Caribe Nautical Services, Inc. (telephone: 305/294-3288; e-mail: kwestships@aol.com). Information received from the Key West Bar Pilots' Association indicated that this schedule provides accurate information regarding dockside arrival and departures. Cruise ships arriving in the Key West area before their scheduled time, wait offshore unless there is a medical emergency or other urgency that requires deviation from normal security procedures. There is a one-hour transit time to the docks from the seabuoy that is approximately 6.5 miles from the docking area.

Water level data, weather data, and the cruise ship schedule for October 2003 appear in Appendices F, G, and H, respectively.

3 Results and Discussion

Before presenting and discussing the turbidity data and graphs, it is important to understand the performance characteristics of the instrumentation used to collect the data from unattended stations. It also is important to understand the movement of water in and around Key West Harbor to more accurately interpret the graphed data.

3.1 Performance of the 4-Beam Turbidity Sensor

During the planning and implementation phases of the monitoring effort, various questions and concerns were identified regarding turbidity sensor performance and procedures to be used in the background monitoring program. During the planning stage, discussions occurred among the team members regarding an acceptable cleaning and calibration frequency for the deployed instruments. After discussion with the equipment manufacturer, a two-day interval was selected for equipment servicing.

While performing the background monitoring, it was noted during calibrations that the 1-second instrument readings would tend to drift up and down around a central value for the Formazin standards. However, when the instrument was being calibrated to zero in filtered, deionized water, drift would only occur from zero to the positive direction because the instruments are programmed not to display negative values.

During monitoring, another phenomenon was noted for some instruments, particularly those attached to buoys in high-energy environments. These instruments would experience intermittent power failures called "fretting" by Hydrolab personnel. Occasionally the turbidity reading before or after such power losses would be suspect given the consistency of the other data collected before and after the power loss. Power losses are responsible for some of the noticeable gaps in the graphed data, particularly on the time-averaged graphs later in the month for Stations E-KWT03-5, -8, and -9.

3.1.1 Stability in the Field

Unattended instruments that are redeployed repeatedly may display changes that related to adjustments made during servicing as well as changes that occur while they are deployed. Both types of changes were apparent during this monitoring effort.

A number of stations, particularly Stations E-KWT03-1, -2, and -7, had a gradual increase in baseline during some of the two-day deployments. These increases did not appear to be related to weather or other long-term factors that might change levels of turbidity. An example of this gradual increase can be seen in the data for Station E-KWT03-7 for the October 24 to 26 time period. This increase might be attributed to instrument fouling caused by biological growth on the turbidity sensors. This baseline increase is noticeable because of the immediate drop in readings after the instruments were serviced and the sensors wiped clean. After redeployed, the baseline typically decreases approximately two to three NTUs. Field notes included descriptions of a greenish algal growth being removed from the sensors during servicing. It was noticed that stations located in swifter moving waters did not experience as much fouling as the stations located within quiescent waters.

Another noticeable baseline phenomenon occurred twice during which the baseline increased approximately 3 to 5 NTU immediately upon being serviced and deployed and then, two days later after the next servicing, the baseline immediately dropped by approximately the same amount it had increased. Systematic field error appears unlikely because of the time overlap of one increasing and one decreasing baseline during the same day that two other instruments calibrated normally. This sustained increase in the baseline, or baseline displacement, may have been caused during the "zeroing" process of the calibration procedure. Any future unattended monitoring should review and revise the calibration procedure to address this phenomenon.

Graphed data were used as one approach to evaluate instrument stability in the field and to approximate the level of precision typical of the field-deployed instruments. After completion of the field work, turbidity data were graphed and the graphs were reviewed for six-hour blocks of data during which turbidity levels would be above 0 NTU and would appear to remain unchanged. While it may be unrealistic to assume that turbidity levels would remain unchanged at any station for six hours, such an evaluation does provide a measure of the level of precision of which the instruments are capable, although likely not the best of their capabilities. It also provides a working measure against which data of suspect accuracy could be objectively evaluated for removal from the data set.

Seven 6-hour periods were identified from five different stations during the October 16 to 22 time period. One six-hour period started immediately after an instrument was serviced and was actually 5 hours and 30 minutes. For the seven data sets, the mean values ranged from 1.0 to 2.7 NTU and the standard deviations ranged from 0.28 to 0.45 and averaged 0.356 for all seven data sets. The range, i.e., the maximum value minus the minimum value, for the seven data sets were 1.7 to 2.3 NTU and averaged 2.01 NTU. From these data, it would appear that the 95 percent confidence level would be 0.7 NTU above and below a reported value. The data from which these statistics were calculated appear in Appendix I as a spreadsheet titled KW-FieldPrecision1.xls.

3.1.2 Instrument Accuracy and Precision

After monitoring had been completed and the equipment had been returned to the base of operations in Gainesville, Florida, eight Hydrolabs were used to estimate the accuracy and precision of the turbidity data collected and to determine if power losses affected more than the readings immediately before or after power loss messages in the data files. After calibrating these Hydrolabs using the field procedures they were programmed to collect turbidity data each minute with 30-second stirrer activation and 30-second sensor warm-up times. The sensors then were placed in Formazin standards of 5 and 20 NTUs for over 30 minutes each. While placed in the Formazin standards, each instrument was walked around and shaken for a two-minute period in an effort to elicit power losses and associated data inaccuracies.

Some readings were recorded over a period exceeding two hours and there appeared to be a trend of decreasing turbidity. This trend was interpreted to be caused by the settling of particulates for the Formazin suspension and the subsequent insufficiency of the intermittent stirring to re-suspend the particles. Collected data can be found in Appendix I.

In an effort to minimize the settling trend of the standards, accuracy and precision calculations were made using only the first 30 data collected from each Formazin standard. Using data from all eight instruments, the mean value for the 5 NTU standard was 4.2 NTU with a standard deviation of 0.44 NTUs. For these 240 values, the minimum was 2.4 NTU and the maximum value was 5.2 NTU. For the 20 NTU standard, the mean was 18.8 NTU with a standard deviation of 0.91 NTU, and the minimum and maximum were 16.7 and 21.4 NTU.

The manufacturer's accuracy range is the true value plus and minus 1 NTU + 5 percent of the reading. The mean values for the 5 and 20 NTU standards appear to be within the manufacturer's accuracy specification. None of the individual turbidity readings were above the upper end of the accuracy range. Of the 44 individual readings that were below the accuracy range for the 5 NTU standard, 42 of them came from two instruments. All 47 readings below the accuracy range for the 20 NTU standard came from the same two instruments and one other.

The 4-Beam Turbidity Sensor is calibrated first to "0" with turbidity-free water and then with a "slope" turbidity standard. Initially, a 20 NTU standard was used in the field and, after experiencing "calibration failure" messages, re-setting the sensors, and discussions with Hydrolab personnel, the slope standard was changed to 50 NTUs which appeared to resolve the problem.

Review of the field data collected shows that at times there are abrupt background turbidity level changes associated with cleaning and recalibration of the instruments. Such events can be seen on the data graphs where breaks in the data stream of typically 20 to 60 minutes occurred due to servicing of the instruments. Such changes may be the result of sensor fouling from accumulation of biological growth and other substances and/or to an inaccuracy associated with a setting the zero calibration point. The results of this brief accuracy and precision testing of eight instruments indicates that setting the zero calibration point may be the cause of at least some of the abrupt shifts in the background readings in the field.

3.1.3 Power Loss Impact on Data

During the accuracy and precision testing of the eight instruments, four generated power loss messages during their stress tests. Three generated two messages and each of the four reported a "zero" turbidity value after one of the power loss episodes. None of the other data appeared to be affected which is consistent with the evaluation of the monitoring data.

Hydrolab personnel were consulted about intermittent power losses and various corrective actions were implemented including reseating electrical connections, use of a dielectric compound between batteries, and use of cushioning material in the protective housings. These actions appeared to be marginally successful.

3.2 Observed Water Masses

During the month of October, there were several occasions when differing water masses were observed and photographed. These occurrences appeared to be related to:

- water passing through Fleming Key Cut on a falling tide
- water flowing from south of Key West through Key West Harbor
- water associated with use of ship thrusters

On several occasions, weed lines were observed in the Key West Harbor area occurring in a north-south orientation. These weed lines appeared to delineate the east-west boundary of different water masses that generally flowed south between Key West and the islands to its west.

Figure 2 is a photograph taken on October 19, 2003, showing such a weed line. However, no turbidity differences for water on either side of the weed line were documented.

On October 23, 2003, a water mass that was lighter in appearance was observed moving into Key West Harbor on a rising tide. Figures 3 and 4 show two views of these water masses. Figures 5 and 6 are photographs taken on October 26, 2003, and show a similar lighter-appearing water mass flowing past the darker water in Truman Harbor and Fleming Dock Bay. It is noteworthy that at Fleming Dock Bay Figure 6, Station E-KWT03-2 is surrounded by the lighter water mass while Station E-KWT03-1 is behind the photographer in the darker water. This observation should be considered when selecting compliance monitoring stations for dredged material off-loading operations.

When cruise ships arrive and depart Key West Harbor, bow and stern thrusters are commonly used for docking and undocking and to turn ships around during departure. Typically dock-side thrusting and turning operations each require approximately 10 minutes to complete. These thrusters can generate strong currents and re-suspend sediment material from the bottom creating turbidity plumes. Figure 7 shows a thruster-generated plume after the lighter-appearing water mass, shown in Figures 5 and 6, had entered the harbor on October 26, 2003.

Turbidity levels associated with these observations are presented and/or discussed in Sections 3.3.3 to 3.3.5.

3.3 Turbidity Levels

This background turbidity monitoring effort was designed to generate data from areas that potentially would be affected by future dredging operations. It was intended to identify examples of phenomena, e.g. weather, tides, and ship traffic, which might relate to the interpretation of future compliance monitoring of dredging operations. A detailed and labor-intensive evaluation of the entire data set was not intended and is not provided.

3.3.1 Management of the Turbidity Data

Data were downloaded from the monitoring instruments as text files before conversion to Microsoft Excel® files. After conversion, data were edited to remove readings collected when the units were not deployed as well as data that subjectively appeared to be inconsistent with other collected data based on the measures of precision described in Sections 3.1.1 and 3.1.2. Such suspect data might be generated as a result of a power loss that was associated with a message in the text file or by small marine organisms attracted to the enclosed space of the weighted sensor guard for which there is no documentation. Removing data from the data set was performed after careful deliberation and typically involved the removal of single data points that caused single, notable peaks or valleys that were excursions from the body of many data appearing before and after it.

On rare occasions, periods of elevated readings, e.g. 100 to 600 NTUs, were found at stations without plausible explanations, e.g., ship thrusters. These data were removed when they were believed to not be representative of the station being monitored.

All downloaded text files with the turbidity monitoring data appear in their entirety in Appendix D. Spreadsheets used to manage and graph the data also appear in Appendix D.

3.3.2 Grouping Stations to Present Turbidity Data

Because of the voluminous amounts of turbidity and ancillary data, combined graphs were prepared in three logical groups to allow useful comparisons. They also have been graphed using two different methods. One set of graphs shows all data that was collected at two-minute intervals.

The second set of graphs presents the data as 8-minute rolling averages. The graphs present the data as calculated values using the average of the time plotted, the two values collected before it and the two values collected after it. Graphs presenting rolling average data tend to dampen the noise associated with instrument readings in systems where abrupt changes are unlikely to occur or occur on an infrequent basis. For the Key West Harbor vicinity, weather induced changes in turbidity would be considered gradual in the context of two-minute readings while turbidity level changes associated with ship thrusters would be abrupt and better evaluated on the graphs presenting the two-minute data.

Eight stations were selected that cover a length of harbor channel that extends from almost two miles south of the island of Key West to the mouth of the bay at the Fleming Key Gunner Dock. These stations are presented on figures in two groupings that are related to tidal flow and the docking area of the cruise ships. The docking area was monitored closely by two stations. Station E-KWT03-4 was located at the northern fender of the Mallory Dock where cruise ships dock. Cruise ships also dock at Dock B and arrivals and departures from these two docks are plotted on the figure for Station E-KWT03-4. Station E-KWT03-6 was located at the Mole Pier and ship arrivals and departures for this location are displayed on the figure for this station. Both of these stations required repairs from damage that is believed to have been caused by the force of the water passing from ship thrusters.

The figures titled "South of Docks" provide a comparison of turbidity levels as water on a falling tide flows south through the harbor by Station E-KWT03-8, west of Fort Taylor, and toward Stations E-KWT03-9 and E-KWT03-10, south of the island.

Figures titled "North of Docks" provide a similar comparison for a rising tide when water generally flows north from the docking area toward Station E-KWT03-3 at the south end of the turning basin and the mouth of the bay at Fleming Key. Station E-KWT03-5 was located west of Malloy Dock and across the channel. It also is shown on the North of Docks set of figures.

The third station grouping for graphing purposes is titled "Protected Areas." Two stations were located in protected water bodies and their data are shown with turbidity levels from the channel stations nearest to them. Station E-KWT03-1 was located on the Gunner Dock in the bay on Fleming Key. Station E-KWT03-2 was located at the mouth of the bay, midway to Man Of War Harbor. Station E-KWT03-7 was located at the NOAA docks in Truman Harbor and was closest to Station E-KWT03-6 on the Mole Pier. From observations made during field activities, there appears to be limited exchange of water between the channel and these two protected areas.

3.3.3 Turbidity Patterns Associated with Tides and Water Currents

Calm weather with winds generally less than 10 mph occurred from October 9 to the early morning of October 15, 2003. Figure 8 shows turbidity data for this time period for Stations E-KWT03-3, -4, -5, -8, and -10. During this period turbidity levels were generally less than 5 NTUs except when ship traffic was present. From Figure 8, it can be seen that the maxima of the turbidity plots coincide with the low tides. This calm weather tidal pattern shows the range of turbidity typically varying by 2 to 3 NTUs during a tidal cycle.

During the same October 9 to 15 time period, a daily pattern was seen at Stations E-KWT03-1 and -7, installed in protected areas at the Fleming Key Gunner Dock and at a NOAA dock in Truman Harbor, respectively. At these two stations, maxima of turbidity levels generally occurred in the morning, between 6 AM and noon, as can be seen in Figure 9. Many of these maxima show rapid increases and/or decreases. It is possible that these increases in turbidity were caused by a daily migration of marine organisms, e.g., plankton, through the water column.

As described in Section 3.2, weed lines were observed in harbor area. After review of the graphed data, no obvious differences in turbidity levels were discerned that might be associated with different water masses in the harbor. However, lack of documented differences may be a result of insufficient ancillary information regarding weed line locations and times as well as placement of monitoring stations. Consequently, there is insufficient information at this time to determine if these different water masses are ever disparate relative to turbidity levels. If they ever are, there is a potential for significant impacts regarding the interpretation of monitoring data for future dredging operations.

3.3.4 Turbidity Patterns and Weather

One measure of weather impacts on turbidity levels in the harbor was made by evaluating data from selected stations during calm and rough conditions. Stations 3, 6, and 8 were selected for use because the instruments at these stations calibrated consistently, were relatively problem-free during the time periods of interest, and were located in the harbor area that likely would experience the same weather-related impacts. No adjustments in the data sets were made for ship-related turbidity impacts.

The four days of October 13 to 16 were selected to represent the calm weather days that came at the end of a several-day period of less than 5 mile per hour winds. Three days, October 26, 27, and 28, were selected as the time period during which weather with winds generally 10 to 15 mph from the east and south caused rough sea conditions.

Out of 6,915 measurements made during the calm period, the mean turbidity value was 0.79 NTU, the median value was 0.70 NTU, and the maximum was 11.2 NTU. For the rough conditions, there were 5,545 measurements with mean, median, and maximum values of 3.72, 3.20, and 18.2 NTU, respectively. Consequently, during the period of rough conditions experienced in October 2003, turbidity levels were approximately three to four times higher than during the selected calm weather period.

As shown in Section 3.3.3, turbidity maxima can at times coincide with tidal minima during periods of calm weather. During windy conditions in late October, a different weather-related effect was observed. It appeared that heavy winds re-suspended sediments along the south coast of Key West and carried them into the harbor channel area on the west side of the island. After a full day of 10 to 15 mph winds from the east, a dramatic increase in turbidity was measured at many stations beginning with the rising tide of the morning of October 26. Using 8-minute rolling averages, Figure 10 shows the turbidity levels increasing in a range of 2- to 6-fold over approximately an hour at Stations E-KWT03-2, -3, -4, -5, and -6. Figure 11 shows the same phenomenon at Stations E-KWT03-8, -9, and -10. This pattern occurred again during the second rising tide of the day for all stations except Stations E-KWT03-9 and -10, which are located along the channel south of the island. Figures 3 and 4, discussed in Section 3.2, might actually show this phenomenon that occurred too late in the tidal cycle on October 23 to reach the monitoring stations.

The speed at which the mass of turbid water moved through the harbor with the first rising tide of the day was calculated using the distances between stations and the time that the leading edge passed each station. The calculated speeds between Station E-KWT03-8 and Stations E-KWT03-5 and -3 were 0.76 and 0.58 mph, respectively. These three stations were located at the edge of the harbor channel and would be most likely to experience "plug flow" of water through the harbor.

The speeds between Station E-KWT03-8 and Stations E-KWT03-6 and -4 were calculated to be 0.37 and 0.44 mph, respectively. These latter two stations were located near the edge of the water where average water speed might have been reduced by drag and eddy currents created by seawalls, docks, and riprap.

The calculations for the second high tide of the day were complicated by the departure of two ships near the time that the turbid water mass began to flow through the harbor.

3.3.5 Turbidity Patterns Associated with Ship Traffic

All graphed turbidity data appear in Appendix A. Selected graphs are presented in this section to identify examples of ship related turbidity impacts and to assist in their evaluation and interpretation.

Cruise ship traffic has been seen to create turbidity plumes during transit between the outer sea buoy and the docks in the harbor, a passage that is typically an hour long. Additional re-suspension of sediment that elevates turbidity levels occurs with the use of bow and stern thrusters during docking, undocking, and turning the ships during departures. During rising tides, water flows northward through the harbor carrying turbidity plumes with it; falling tides carry turbidity plumes southward through the harbor. During transit, cruise ships pass near Stations E-KWT03-8, -9, and -10 although water flow conditions may move turbidity plumes toward, or away from, these stations.

Figures of plotted turbidity data identified as "North of Docks" and "South of Docks" all present data for five stations for time periods of 3.25 days, with quarter-day overlap of consecutive figures. Stations on these figures are presented in a north to south arrangement down the page to assist interpreting the data in the context of tidal flows.

The eight-minute rolling time-averaged graphs are usefully when evaluating events of intermediate to long-term duration. For events that may occur over a few minutes, the data plots without averaged data are more useful. Because they show actual data, the two-minute data plots will display higher peak values because the highest values are not averaged with the lower values measured before and/or after them.

Figure 12 shows the two-minute data that were previously presented as rolling averages on Figure 10. There are several turbidity peaks that appear to be associated with ship activity on Figure 12. Two ships docked on October 24 at 0600 and 0630 (EDT) during a rising tide, which coincide with, or slightly precede, turbidity peaks at Stations E-KWT03-2, -3, -4, and -5. On October 26, three ships arrived between 1200 and 1230 causing turbidity peaks at all but the northern-most station on this figure. Figure 7 is a photograph taken near noon of a ship docking at the Mallory Dock by Station E-KWT03-4. Station E-KWT03-3 is in the center of the photograph toward which the plume was moving; however, the tide may have changed before this plume reached Station E-KWT03-2 at the mouth of Fleming Key Bay. It is possible that the smaller peaks shown at Stations E-KWT03-3 and -5 at approximately 1500 hours are the residual plume that was being carried passed these stations on the falling tide. The peak turbidity values that are shown to be off-scale for this figure were: Station 5 on 10/24 at 0730 - 28.6 NTU; Station 4 on 10/26 at 1144 - 25.0 NTU, and Station 5 on 10/26 at 1924 - 25.9 NTU.

Figure 13 shows the same two-minute data that are shown as time-averaged data on Figure 11. Ships departing during a falling tide on October 24 at 1400 appear to be responsible for turbidity peaks at the three southern stations. The turbidity peak occurred at Station E-KWT03-10 over a 20-minute period, i.e., between 1444 and 1504 with the highest value being 23.8 NTU. The sharpness of this peak may indicate that the plume was compact and measured immediately after the ship passed by rather than having been dispersed as it was carried a long distance by tidal flow.

Sharp peaks with different time spans occurred at Station E-KWT03-10 during the October 12 to 15 time period and can be seen on Figure 14. Slack tide may occur at this station slightly earlier than at Truman Harbor where the plotted water elevation data are collected. Turbidity peaks, associated with two ships arriving before noon on October 12 and one ship departing before midnight that night, are broader (averaging 29 minutes), with lower maximum readings, than the sharper peaks (averaging 15 minutes) associated with ship traffic slightly after the tidal change on October 12 at 1800 and on October 15 at 0100. This figure also shows that while peaks may be measured at several stations for a single ship movement (e.g., at four stations around 0200 on October 15) other ship events may be recorded at only a single station.

One general observation is that ship-related events appeared to be recorded more frequently and at a higher magnitude at Station E-KWT03-10 than at Stations E-KWT03-8 and -9. Sediment characteristics and/or ship speed may differ at stations and might explain this observation.

Another general observation is that Station E-KWT03-2 at the mouth of the bay on Fleming Key appears to be on the edge of the flow of water passing through Man Of War Harbor. Often it was not possible to associate any peaks at this station to ship activities.

Quite often differences between ship arrival and departure times and time of turbidity peak readings follow a pattern expected because of current-driven travel time from the plume source to the monitoring stations. Stations E-KWT03-4 and -6 were located at docks near the water-dock interface. Water passing these two stations may have experienced drag and eddy currents that increased travel time relative to Stations E-KWT03-3, -5, and -8 that were much farther from land and at the edge of the navigational channel.

3.4 Water Current Speeds and Directions

Data were retrieved for 28 deployments of the drogue. After editing for boat-related influences during deployment and retrieval, the final data sets spanned 10 to 76 minutes. Table 2 shows summary information from each drift and Figures 15, 16, and 17 present the data plotted on maps using Mercator projection. All current monitoring data appear in Appendix E.

As shown on Figures 15 and 16, eight drifts were performed in the Fleming Dock Bay and two drifts occurred in Truman Harbor. These drifts were performed, in part, to obtain information regarding wind and surface water effects on the surface float in relatively quiescent water to identify the potential magnitude of any resultant impacts on drogue movement. Truman Harbor is a protected area with a relatively small opening for the tidal exchange of water. Fleming Dock Bay is a small shallow bay and, at times, observations have shown that tidally driven water tends to flow past it without obvious intrusions at the surface. The results of the ungrounded drifts in Truman Harbor and the bay found that the drogue moved between averaged speeds of 0.10 to 0.24 mph with wind speeds of 10 to 20 mph. As seen on Table 2, the direction of the drogue movement coincides with wind direction.

Drifts X and AB within Fleming Dock Bay were completely grounded and could not be used to estimate measurement bias caused by wind or surface currents. They are included here to show the precision associated with the DGPS measurements.

During Drifts U and V, the bottom appeared to have been encountered to an extent that the entire sets of data are not believed to be representative of free-drifting conditions. Portions of Drifts U and V appeared to be free of grounding effects and drift speeds were calculated using partial data sets.

Eighteen drifts were performed with the drogue in various locations around Key West Harbor, the entrance channel, and by Tank Island. Average current speeds ranged from 0.29 to 1.8 mph with wind speeds of 3 to 18 mph.

Many of the current direction lines are seen on Figures 16 and 17 appear to curve slightly. Drift O on Figure 16 shows the greatest amount of direction change. This drift was performed during a falling tide and began in the Fleming Key Cut with a wind blowing from the northwest. Drift O ended with the drogue being caught in an eddy current west of the Coast Guard piers (see insert in Figure 16. Because the drogue was deployed near the north side of the Fleming Key Cut channel, it appears that the 10 mph northwest wind caused the drogue to move across the channel current during the approximately 14-minute, 0.36-mile travel to the area of the eddy current. Assuming a 200-foot cross-current drift, wind and surface current stress on the surface float may have caused an error vector, or bias, of approximately 0.16 mph to the southeast.

After retrieving the drogue from Drift O, it was released for Drift P approximately 350 feet to the west-northwest of the end of Drift O. This location was near a weed line that appeared to delineate the water mass flowing from Fleming Key Cut and water flowing from the Man Of War Harbor area. During Drift P, the drogue started at a speed of ~2.0 mph, slowed midway to approximately 0.8 mph and finished at slightly greater than 4.0 mph.

As with Drift P and many other drifts, the drogue often was found to move at gradually changing speeds, possibly because of changing tidal stage and by the islands acting as barriers to linear water flow. Drift M was 47 minutes in duration, ending at 0908 EDT, and was performed near the end of a rising tide (high tide at Truman Harbor was recorded near 1006 EDT). Drogue movement steadily declined from approximately 0.8 mph to near 0.4 mph. Drift N was started soon after Drift M at 0930 on an observed falling tide and the measured drogue speed increased from near 0.2 mph to approximately 0.8 mph over 36 minutes.

Drift J began near Fort Taylor at 1.6 mph and declined with distance from the island to approximately 0.9 mph over a 36-minute period. Drift K began approximately one hour after Drift J and ended after 46 minutes with drogue movement decreasing in speed from 2.7 mph to approximately 1.0 mph as it moved farther from the island.

4 Conclusions

4.1 Performance of the 4-Beam Turbidity Sensor

Calibration of the 4-Beam Turbidity Sensor before unattended deployment appeared to be somewhat problematic because of the inability to fix the zero calibration accurately each time. Because these sensors are designed for low-level measurements, the one-per-second measurements displayed during the calibration process produce readings that fluctuate about a central value and fixing the "zero" response is complicated by the inability to see negative responses associated with fluctuation about the "zero" response. Discussions with the manufacturer in the past regarding pH issues have resulted in instrument programming changes and this approach might be pursued for this turbidity calibration issue.

This "zero" calibration issue may be related to the slightly low values for the 5 and 20 NTU check standards after calibrating with a 50 NTU slope standard. Mean values for these check standards were 4.2 and 18.8 NTU, respectively.

Precision of the 4-Beam Sensor was found to be acceptable for monitoring needs. In a controlled environment, the average standard deviations for repetitive measurements of the 5 and 20 NTU Formazin standards using eight instruments were 0.44 NTU and 0.91 NTU, respectively. These results might be biased high because of potential settling of the standards during the measurement period. During seven 6-hour periods of relatively consistent readings in the field, turbidity measurements were found to vary with a average standard deviation of 0.356 NTU and 95 percent of the data were calculated to fall within 0.7 NTU of a mean reading.

Some fouling of the sensors appears to have occurred over the typical 2-day deployment period. Such fouling was attributed to the colonization of the sensor surface by marine microorganisms and occurred in the protected and more quiescent water at Stations E-KWT03-1 and -7.

Power loss error messages were reported by instrument in the higher energy environments. Typically such errors would result in the loss of no more than a single turbidity reading per power loss; however, multiple power losses can result in the loss of a large amount of data. Redesign of the protective housings for the instruments might reduce these occurrences in the future. Power loss occurrences are not expected to be a problem when these instruments are used by field personnel, e.g., during compliance monitoring, and not deployed for unattended monitoring.

4.2 Observed Water Masses and Currents

Two types of distinctive water masses were observed during the October 2003 monitoring effort: those delineated by weed lines and those with well-defined differences in appearance.

On falling tides, water flowing westward through Fleming Key Cut at times would meet water flowing from north and/or northwest of the harbor and establish a weed line that appeared to delineate the boundary of the water masses. These observations provide useful information that a reoccurring phenomenon exists; however, insufficient information was obtained on water masses defined by weed lines to be useful for interpreting compliance monitoring data from future dredging activities.

During times of strong winds from the east and south, distinctively more turbid water from south of the island of Key West would be drawn into the harbor area during rising tides. These occurrences were documented by photography and by the monitoring equipment. These turbid water masses also showed that the water masses in Truman Harbor and the bay on Fleming Key are somewhat isolated from the tidal flushing of the harbor channel area.

Current monitoring showed that, as expected, water does not move in straight lines around the harbor and island areas. Flow directions between Key West and the two islands to the west are predictable based on tides. Flow directions south of the island might be controlled by both wind and tides and are less predictable. Typical average current speeds were between 0.4 and 1.8 mph for the time periods that the current monitor was deployed.

4.3 Turbidity Patterns and Events

Patterns in turbidity level changes were identified and appear to be associated with daily cycles, tidal fluctuations, weather changes, and large ship traffic.

Daily patterns of turbidity increases and decreases were seen to occur over a period of several days in the protected waters of Truman Harbor and the bay at Fleming Key at Stations E-KWT03-1 and -7. These broad turbidity peaks showed a change of 2 to 3 NTUs occurring between 0600 and noon on a daily basis. This pattern was identified when wind conditions usually averaged less than 5 mph. This daily pattern was not identified at any of the other stations.

Turbidity patterns associated with the tidal cycle were most noticeable during calm weather conditions. Broad turbidity peaks were observed to coincide with the low tide as recorded at Truman Harbor. These peaks typically were changes of 1 to 3 NTUs above the high tide turbidity levels.

In late October, 10 to 20 mph winds from the east and south appear to have formed a mass of turbid water south of Key West. This water mass was driven into Key West Harbor by rising tides increasing turbidity levels in the harbor by 5 to 10 NTUs. Photographs of these events document the visual differences between the water masses.

During the month of October 2003, a few well-defined weather scenarios were experienced. These weather events (e.g., calm conditions, continued 10 to 20 mph south and east winds) provided an opportunity to describe and/or measure their impacts on turbidity levels in the vicinity of the harbor. During the September 2001 monitoring, strong winds produced higher area-wide levels of turbidity than were found during this investigation. Therefore, it is quite likely that other weather patterns that have not been observed, e.g., continued strong winds from the northwest or west, are likely to produce changes in turbidity levels that will complicate the interpretation of future compliance monitoring data.

Cruise ships were found to create turbidity plumes that typically were of short duration. Because of their short duration, ship related turbidity contributions should be evaluated using graphs of the actual data, collected at two-minute intervals, rather than 8-minute rolling average graphs. Rolling average graphs tend to dampen the maximum peak values by averaging the highest values with lower values.

Ships passed by Stations E-KWT03-8, -9 and -10 when arriving and departing.
Station E-KWT03-10 appeared to record more and higher turbidity peaks than
Stations E-KWT03-8 and -9. As might be expected, stations near or at the docking areas recorded the greatest changes related to ship movement although tidal flow caused these to dissipate rapidly.